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Chapter 3

MAGNETIC, ELECTRIC, AND INSULATION MATERIALS FOR IM

3.1. INTRODUCTION

Induction machines contain magnetic circuits traveled by a.c. and traveling magnetic fields and electric circuits flowed by alternative currents. The electric circuits are insulated from the magnetic circuits (cores). The insulation system comprises the conductor, slot and interphase insulation.

Magnetic, electrical, and insulation materials are characterized by their characteristics (B(H) curve, electrical resistivity, dielectric constant, and breakdown electric field (V/m)) and their losses.

At frequencies encountered in IMs (up to tens of kHz, when PWM inverter fed), the insulation losses are neglected. Soft magnetic materials are used in IM as the magnetic field is current produced. The flux density (B)/magnetic field (H) curve and cycle depend on the soft material composition and fabrication process. Their losses in W/kg depend on the B-H hysteresis cycle, frequency, electrical resistivity, and the a.c. (or) traveling field penetration into the soft magnetic material.

Silicon steel sheets are standard soft magnetic materials for IMs. Amorphous soft powder materials have been introduced recently with some potential for high frequency (high speed) IMs. The pure copper is the favorite material for the stator electric circuit (windings), while aluminum or brass is used for rotor squirrel cage windings.

Insulation materials are getting thinner and better and are ranked into a few classes: A (105°C), B (130°C), F (155°C), H (180°C).

3.2. SOFT MAGNETIC MATERIALS

In free space the flux density B and the magnetic field H are related by the permeability of free space $\mu_0 = 4\pi 10^{-7} \text{H/m}$ (S.I.)

$$B \left[\frac{\text{Wb}}{\text{m}^2} \right] = \mu_0 \left[\frac{\text{H}}{\text{m}} \right] \cdot H \left[\frac{\text{A}}{\text{m}} \right] \quad (3.1)$$

Within a certain material a different magnetization process occurs.

$$B = \mu \cdot H; \quad \mu = \mu_0 \mu_R \quad (3.2)$$

In (3.2) μ is termed as permeability and μ_R relative permeability (nondimensional).

Permeability is defined for homogenous (uniform quality) and isotropic (same properties in all directions) materials. In nonhomogeneous or (and)

nonisotropic materials, μ becomes a tensor. Most common materials are nonlinear: μ varies with B .

A material is classified according to the value of its relative permeability, μ_R , which is related to its atomic structure.

Most nonmagnetic materials are either paramagnetic-with μ_R slightly greater than 1.0, or diamagnetic with μ_R slightly less than 1.0. Superconductors are perfect diamagnetic materials. In such materials when $B \rightarrow 0$, $\mu_R \rightarrow 0$.

Magnetic properties are related to the existence of permanent magnetic dipoles within the matter.

There are quite a few classes of more magnetic materials ($\mu_R \gg 1$). Among, them we will deal here with soft ferromagnetic materials. Soft magnetic materials include alloys made of iron, nickel, cobalt and one rare earth element and/or soft steels with silicon.

There is also a class of magnetic materials made of powdered iron particles (or other magnetic material) suspended in an epoxy or plastic (nonferrous) matrix. These softpowder magnetic materials are formed by compression or injection, molding or other techniques.

There are a number of properties of interest in a soft magnetic material such as permeability versus B , saturation flux density, $H(B)$, temperature variation of permeability, hysteresis characteristics, electric conductivity, Curie temperature, and loss coefficients.

The graphical representation of nonlinear $B(H)$ curve (besides the pertinent table) is of high interest (Figure 3.1). Also of high interest is the hysteresis loop (Figure 3.2).

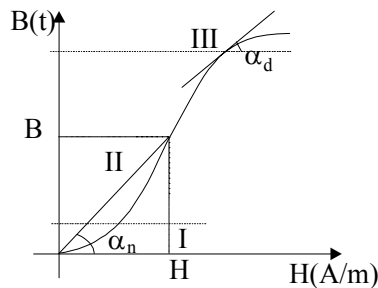


Figure 3.1 Typical B-H curve

There are quite a few standard laboratory methods to obtain these two characteristics. The B-H curve can be obtained two ways: the virgin (initial) B-H curve, obtained from a totally demagnetized sample; the normal (average) B-H curve, obtained as the tips of hysteresis loops of increasing magnitude. There is only a small difference between the two methods.

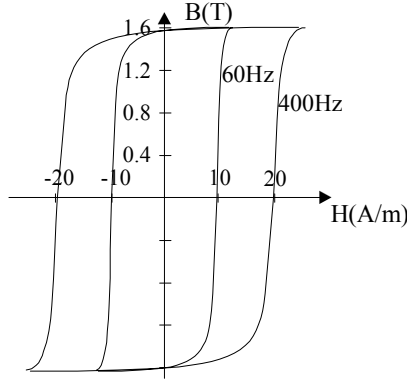


Figure 3.2 Deltamax tape-wound core 0.5 mm strip hysteresis loop

The B-H curve is the result of domain changes within the magnetic material. The domains of soft magnetic materials are 10^{-4} - 10^{-7} m in size. When completely demagnetized, these domains have random magnetization with zero flux in all finite samples.

When an external magnetic field H is applied, the domains aligned to H tend to grow when increasing B (region I on [Figure 3.1](#)). In region II, H is further increased and the domain walls move rapidly until each crystal of the material becomes a single domain. In region III, the domains rotate towards alignment with H . This results in magnetic saturation B_s . Beyond this condition, the small increase in B is basically due to the increase in the space occupied by the material for $B = \mu_0 H_{r0}$.

This “free space” flux density may be subtracted to obtain the intrinsic magnetization curve. The nonlinear character of B-H curve ([Figure 3.1](#)) leads to two different definitions of relative permeability.

- The normal permeability μ_{Rn} :

$$\mu_{Rn} = \frac{B}{\mu_0 H} = \frac{\tan \alpha_n}{\mu_0} \quad (3.3)$$

- The differential relative permeability μ_{Rd} :

$$\mu_{Rd} = \frac{dB}{\mu_0 dH} = \frac{t_{an} \alpha_d}{\mu_0} \quad (3.4)$$

Only in region II, $\mu_{Rn} = \mu_{Rd}$. In region I and III, in general, $\mu_{Rn} > \mu_{Rd}$ ([Figure 3.3](#)). The permeability is maximum in region II. For M19 silicon steel sheets ($B_s = 2T$, $H_s = 40,000$ A/m, $\mu_{Rmax} = 10,000$).

So the minimum relative permeability is

$$(\mu_{Rn})_{B_s=2.0T} = \frac{2.0}{4\pi 10^{-7} \cdot 40000} = 39.8! \quad (3.5)$$

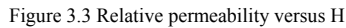


Table 3.1. B-H curve for silicon (3.5%) steel (0.5mm thick) at 50Hz

Table 3.2.[illegible]

It has been shown experimentally that the magnetization curve varies with frequency as in Table 3.2. This time the magnetic field is kept in original data (Oe = 79.55A/m). [1]

In essence the magnetic field increases with frequency for same flux density B. Reduction of the design flux density is recommended when the frequency increases above 200 Hz as the core losses grow markedly with frequency.

3.3. CORE (MAGNETIC) LOSSES

Energy loss in the magnetic material itself is a very significant characteristic in the energy efficiency of IMs. This loss is termed core loss or magnetic loss.

Traditionally, core loss has been divided into two components: hysteresis loss and eddy current loss. The hysteresis loss is equal to the product between the hysteresis loop area and the frequency of the magnetic field in sinusoidal systems.

$$P_h \approx k_h f B_m^2 [W/kg]; \quad B_m - \text{maximum flux density} \quad (3.6)$$

Hysteresis losses are 10 to 30% higher in traveling fields than in a.c. fields for $B_m < 1.5(1.6)T$. However, in a traveling field they have a maximum, in general, between 1.5 to 1.6T and then decrease to low values for $B > 2.0T$. The computation of hysteresis losses is still an open issue due to the hysteresis cycle complex shape, its dependence on frequency and on the character of the magnetic field (traveling or a.c.) [2].

Preisach modelling of hysteresis cycle is very popular [3] but neural network models have proved much less computation time consuming. [4]

Eddy current losses are caused by induced electric currents in the magnetic material by an external a.c. or traveling magnetic field.

$$P_e \approx k_e f^2 B_m^2 [W/kg] \quad (3.7)$$

Finite elements are used to determine the magnetic distribution-with zero electrical conductivity, and then the core losses may be calculated by some analytical approximations as (3.6)-(3.7) or [5]

$$P_{core} \approx k_h f B_m^\alpha K(B_m) + \frac{\sigma_{Fe}}{12 \gamma_{Fe}} \int_{1/f} \left(\frac{dB}{dt} \right)^2 dt + K_{ex} f \int_{1/f} \left(\frac{dB}{dt} \right)^{1.5} dt \quad (3.8)$$

$$\text{where} \quad K = 1 + \frac{0.65}{B_m} \sum^n \Delta B_i$$

B_m -maximum flux density

f -frequency

γ_{Fe} -material density

d -lamination thickness

K_h -hysteresis loss constant

K_{ex} -excess loss constant

ΔB_i -change of flux density during a time step

n -total number of time steps

Equation (3.8) is a generalization of Equations (3.6) and (3.7) for nonsinusoidal time varying magnetic fields as produced in PWM inverter IM drives.

For sinusoidal systems, the eddy currents in a thin lamination may be calculated rather easily by assuming the external magnetic field $H_0 e^{j\omega_1 t}$ acting parallel to the lamination plane (Figure 3.4).

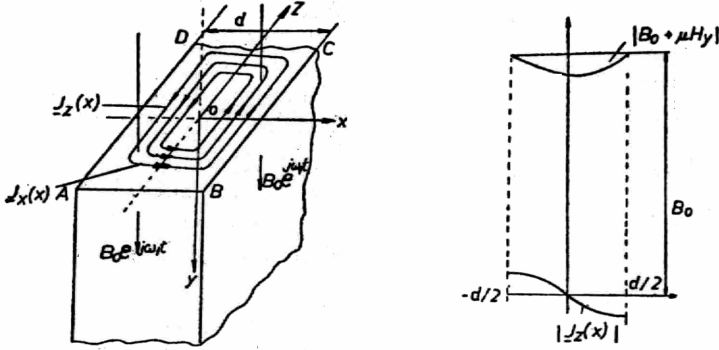


Figure 3.4 Eddy currents paths in a soft material lamination

Maxwell's equations yield

$$\begin{aligned} \frac{\partial H_y}{\partial x} &= J_z; \quad H_{0y} = H_0 e^{j\omega_1 t} \\ -\frac{\partial E_z}{\partial x} &= -j\omega_1 \mu (H_{0y} + H_y); \quad \sigma_{Fe} E_z = J_z \end{aligned} \quad (3.9)$$

where J is current density and E is electric field.

As the lamination thickness is small in comparison with its length and width, J_x contribution is neglected. Consequently (3.9) is reduced to

$$\frac{\partial^2 H_y}{\partial x^2} - j\omega_1 \mu \sigma_{Fe} H_y = j\omega_1 \sigma_{Fe} B_0 \quad (3.10)$$

$B_0 = \mu_0 H_0$ is the initial flux density on the lamination surface.

The solution of (3.10) is

$$H_y(x) = A_1 e^{\gamma x} + A_2 e^{-\gamma x} + \frac{B_0}{\mu_0} \quad (3.11)$$

$$\gamma = \beta(1 + j); \quad B = \sqrt{\frac{\omega_1 \mu \sigma_{Fe}}{2}} \quad (3.12)$$

The current density $J_z(x)$ is

$$J_z(x) = \frac{\partial H_y}{\partial x} = \gamma(A_1 e^{\gamma x} + A_2 e^{-\gamma x}) \quad (3.13)$$

The boundary conditions are

$$H_y\left(\frac{d}{2}\right) = H_y\left(-\frac{d}{2}\right) = 0 \quad (3.14)$$

Finally

$$A_1 = A_2 = \frac{B_0}{2\mu \cosh \beta \frac{d}{2}(1+j)} \quad (3.15)$$

$$J_z(x) = -\frac{\beta(1+j)}{\mu} \frac{B_0 \sinh(1+j)\beta x}{\cosh \beta \frac{d}{2}(1+j)} \quad (3.16)$$

The eddy current loss per unit weight P_e is

$$P_e = \frac{2\gamma_{Fe}}{d\sigma_{Fe}} \frac{1}{2} \int_0^{d/2} (J_z(x))^2 dx = \frac{\beta\gamma_{Fe}d\omega_1}{\mu} B_0^2 \left[\frac{\sinh(\beta d) - \sin(\beta d)}{\cosh(\beta d) + \cos(\beta d)} \right] \left[\frac{W}{kg} \right] \quad (3.17)$$

The iron permeability has been considered constant within the lamination thickness although the flux density slightly decreases.

For good utilization of the material, the flux density reduction along lamination thickness has to be small. In other words $\beta d \ll 1$. In such conditions, the eddy-current losses increase with the lamination thickness.

The electrical conductivity σ_{Fe} is also influential and silicon added to soft steel reduces σ_{Fe} to $(2-2.5)10^6 (\Omega m)^{-1}$. This is why 0.5-0.6 mm thick laminations are used at 50(60) Hz and, in general, up to 200-300Hz IMs.

For such laminations, eddy current losses may be approximated to

$$P_e \approx K_w B_m^2 \left[\frac{W}{kg} \right]; K_w = \frac{\omega_1^2 \sigma_{Fe} d^2}{24} \gamma_{Fe} \quad (3.18)$$

The above loss formula derivation process is valid for a.c. magnetic field excitation. For pure traveling field the eddy current losses are twice as much for same laminations, frequency, and peak flux density.

In view of the complexity of eddy current and hysteresis losses, it is recommended tests be run to measure them in conditions very similar to those encountered in the particular IM.

Soft magnetic material producers manufacture laminations for many purposes. They run their own tests and provide data on core losses for practical values of frequency and flux density.

Besides Epstein's traditional method, made with rectangular lamination samples, the wound toroidal cores method has also been introduced [6] for a.c. field losses. For traveling field loss measurement, a rotational loss tester may be used. [7]

Typical core loss data for M15-3% silicon 0.5 mm thick lamination material—used in small IMs, is given in Figure 3.5. [8]

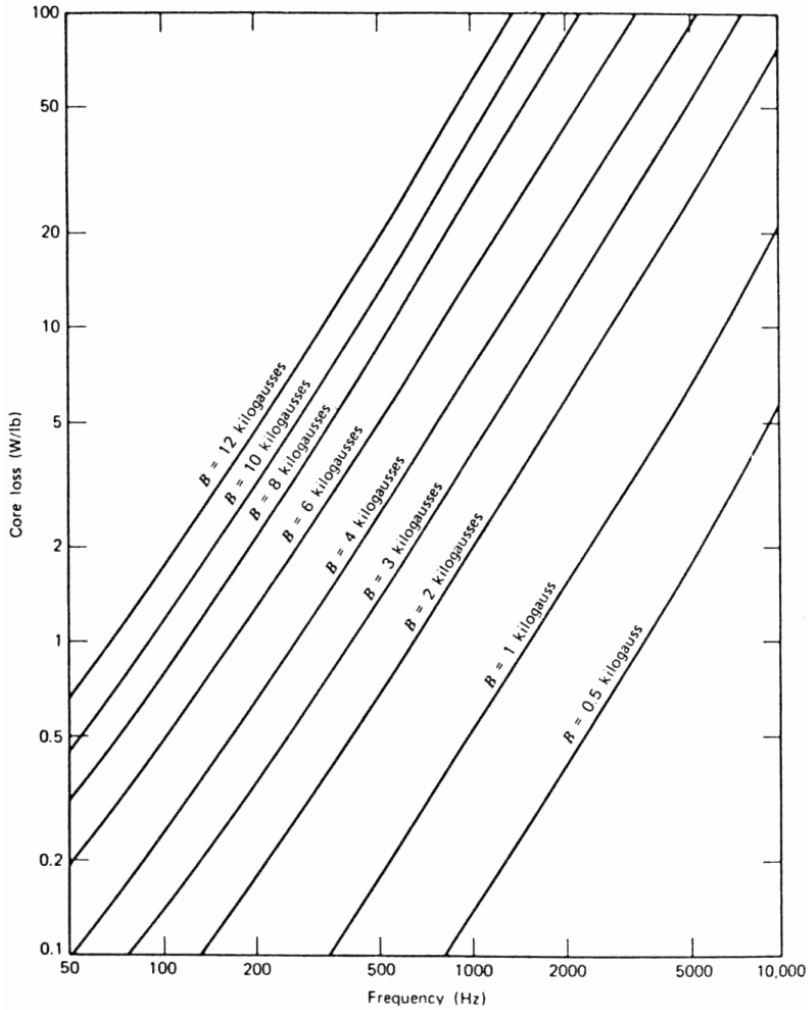


Figure 3.5 Core losses for M15-3% silicon 0.5 mm thick laminations [8]

Table 3.3. [1]

Induction (kC)	50 Hz	60 Hz	100 Hz	150 Hz	200 Hz	300 Hz	400 Hz	600 Hz	1000 Hz	1500 Hz	2000 Hz
1.0	0.008	0.009	0.017	0.029	0.042	0.074	0.112	0.205	0.465	0.900	1.451
2.0	0.031	0.039	0.072	0.119	0.173	0.300	0.451	0.812	1.786	3.370	5.318
4.0	0.109	0.134	0.252	0.424	0.621	1.085	1.635	2.960	6.340	11.834	18.523
7.0	0.273	0.340	0.647	1.104	1.640	2.920	4.450	8.180	17.753	33.720	53.971
10.0	0.494	0.617	1.182	2.040	3.060	5.530	8.590	16.180	36.303	71.529	116.702
12.0	0.687	0.856	1.646	2.860	4.290	7.830	12.203	23.500	54.258	108.995	179.321
13.0	0.812	1.014	1.942	3.360	5.060	9.230	14.409	27.810	65.100	131.918	
14.0	0.969	1.209	2.310	4.000	6.000	10.920	17.000				
15.0	1.161	1.447	2.770	4.760	7.130	13.000	20.144				
15.5	1.256	1.559	2.990	5.150	7.710	13.942	21.619				
16.0	1.342	1.667	3.179	5.466	8.189						
16.5	1.420	1.763	3.375	5.788	8.674						
17.0	1.492	1.852	3.540	6.089	9.129						

As expected, core losses increase with frequency and flux density. A similar situation occurs with a superior but still common material: steel M19 FP (0.4 mm) 29 gauge (Table 3.3). [1]

A rather complete up-to-date data source on soft magnetic materials characteristics and losses may be found in Reference 1.

Core loss represents 25 to 35% of all losses in low power 50(60) Hz IMs and slightly more in medium and large power IMs at 50(60) Hz. The development of high speed IMs, up to more than 45,000 rpm at 20 kW [9], has caused a new momentum in the research for better magnetic materials as core losses are even larger than winding losses in such applications.

Thinner (0.35 mm or less) laminations of special materials (3.25% silicon) with special thermal treatment are used to strike a better compromise between low 60 Hz and moderate 800/1000 Hz core losses (1.2 W/kg at 60 Hz, 1T; 28 W/kg at 800 Hz, 1T).

6.5% silicon nonoriented steel laminations for low power IMs at 60 Hz have been shown capable of a 40% reduction in core losses. [10] The noise level has also been reduced this way. [10] Similar improvements have been reported with 0.35mm thick oriented grain laminations by alternating laminations with perpendicular magnetization orientation or crossed magnetic structure (CMS). [11]

Soft magnetic composites (SFC) have been produced by powder metallurgy technologies. The magnetic powder particles are coated by insulation layers and a binder which are compressed to provide

- Large enough magnetic permeability
- Low enough core losses
- Densities above 7.1 g/cm³ (for high enough permeability)

The hysteresis loss tends to be constant with frequency while the eddy current loss increases almost linearly with frequency (up to 1 kHz or so).

At 400 to 500 Hz and above, the losses in SFC become smaller than for 0.5 mm thick silicon steels. However the relative permeability is still low: 100 to 200. Only for recent materials, fabricated by cold compression, the relative permeability has been increased above 500 for flux densities in the 1T range. [12, 13]

Added advantages such as more freedom in choosing the stator core geometry and the increase of slot-filling factor by coil in slot magnetic compression embedded windings [14] may lead to a wide use of soft magnetic composites in induction motors. The electric loading may be thus increased. The heat transmissivity also increases. [12]

In the near future, better silicon 0.5 mm (0.35 mm) thick steel laminations with nonoriented grain seem to remain the basic soft magnetic materials for IM fabrication. For high speed (frequency above 300 Hz) thinner laminations are to be used. The insulation coating layer of each lamination is getting thinner and thinner to retain a good stacking factor (above 85%).

3.4. ELECTRICAL CONDUCTORS

Electric copper conductors are used to produce the stator three (two) phase windings. The same is true for wound rotor windings.

Electrical copper has a high purity and is fabricated by an involved electrolysis process. The purity is well above 99%. The cross-section of copper conductors (wires) to be introduced in stator slots is either circular or rectangular (Figure 3.6). The electrical resistivity of magnetic wire (electric conductor) $\rho_{Co} = (1.65-1.8) \times 10^{-8} \Omega m$ at $20^\circ C$ and varies with temperature as

$$\rho_{Co}(T) = (\rho_{Co})_{20} [1 + (T - 20) / 273] \quad (3.19)$$

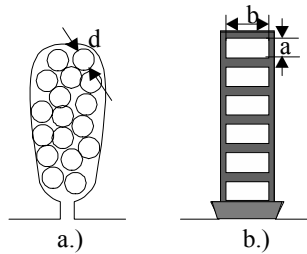


Figure 3.6 Stator slot with round (a) and rectangular (b) conductors

Round magnetic wires come in standardized gauges up to a bare copper diameter of about 2.5mm (3mm) (or 0.12inch), in general (Tables 3.4 and 3.5).

The total cross-section A_{con} of the coil conductor depends on the rated phase current I_{In} and the design current density J_{con} .

$$A_{con} = I_{In} / J_{con} \quad (3.20)$$

The design current density varies between 3.5 and 15 A/mm² depending on the cooling system, service duty cycle, and the targeted efficiency of the IM. High efficiency IMs are characterized by lower current density (3.5 to 6 A/mm²). If the A_{con} in (3.19) is larger than the cross section of the largest round wire gauge available, a few conductors of lower diameter are connected in

parallel and wound together. Up to 6 to 8 elementary conductors may be connected together.

Table 3.4. Round magnetic wire gauges in inches

Avg Size	Bare Wire Diameter (Nominal) (Inches)	FILM ADDITIONS (Inches)		OVERALL DIAMETER (Inches)			WEIGHT AT 20°C-68°F		RESISTANCE AT 20°C-68°F		Wires/in. Nom.	Avg Size
		Min.	Max.	Min.	Nom.	Max.	Lbs./M Ft. Nom.	Ft./Lb. Nom.	Ohms/M Ft. Nom.	Ohms./Lb. Nom.		
8	.1285	.0015	.0025	.1288	.1306	.1324	50.20	19.32	.6281	.01251	7.66	8
9	.1144	.0018	.0026	.1149	.1165	.1181	39.81	25.12	.7925	.01191	8.58	9
10	.1019	.0015	.0025	.1024	.1039	.1054	31.59	31.66	.9088	.01162	9.82	10
11	.0907	.0015	.0025	.0913	.0927	.0941	25.04	39.94	1.26	.05632	10.8	11
12	.0808	.0014	.0024	.0814	.0827	.0840	19.92	50.20	1.59	.07982	12.1	12
13	.0720	.0014	.0023	.0727	.0738	.0750	15.81	63.25	2.00	.11265	13.5	13
14	.0641	.0014	.0023	.0649	.0659	.0670	12.49	90.06	2.52	.2018	15.2	14
15	.0571	.0013	.0022	.0578	.0588	.0599	9.848	100.5	3.18	.3186	17.0	15
16	.0508	.0012	.0021	.0515	.0525	.0534	7.880	126.9	4.02	.5101	19.0	16
17	.0453	.0012	.0020	.0460	.0469	.0478	6.269	159.5	5.05	.8055	21.3	17
18	.0403	.0011	.0019	.0410	.0418	.0426	4.970	201.2	6.39	1.286	23.9	18
19	.0359	.0011	.0019	.0366	.0374	.0382	3.943	253.6	8.05	2.041	26.7	19
20	.0320	.0010	.0018	.0327	.0334	.0341	3.138	318.7	10.1	3.219	29.8	20
21	.0285	.0010	.0018	.0292	.0299	.0306	2.492	401.2	12.8	5.135	33.4	21
22	.0253	.0010	.0017	.0260	.0267	.0273	1.969	507.9	16.2	8.228	37.5	22
23	.0226	.0009	.0016	.0233	.0238	.0244	1.572	636.1	20.3	12.91	42.0	23
24	.0201	.0009	.0015	.0208	.0213	.0218	1.240	806.5	25.7	20.73	46.9	24
25	.0178	.0009	.0015	.0186	.0191	.0195	.988	1017	32.4	32.79	52.4	25
26	.0159	.0008	.0013	.0165	.0169	.0174	.779	1284	41.0	52.64	59.2	26
27	.0142	.0008	.0013	.0149	.0153	.0156	.623	1605	51.4	82.50	65.4	27
28	.0126	.0007	.0012	.0132	.0136	.0139	.491	2037	65.3	133.0	73.5	28
29	.0113	.0007	.0012	.0119	.0122	.0126	.395	2532	81.2	205.6	82.6	29
30	.0100	.0006	.0011	.0105	.0109	.0112	.310	3226	104	335.5	91.7	30
31	.0089	.0006	.0011	.0094	.0097	.0100	.246	4065	131	532.5	103	31
32	.0080	.0006	.0010	.0085	.0088	.0091	.199	5025	162	814.1	114	32
33	.0071	.0005	.0009	.0075	.0078	.0081	.157	6394	206	1317	128	33
34	.0063	.0005	.0008	.0067	.0070	.0072	.123	8120	261	2122	143	34
35	.0056	.0004	.0007	.0059	.0062	.0064	.0977	10235	331	3388	161	35
36	.0050	.0004	.0007	.0053	.0056	.0058	.0783	12771	415	5300	179	36
37	.0045	.0003	.0006	.0047	.0050	.0052	.0632	15823	512	8101	200	37
38	.0040	.0003	.0006	.0042	.0045	.0047	.0501	19960	648	12934	222	38
39	.0035	.0002	.0005	.0036	.0039	.0041	.0383	26110	847	22115	256	39
40	.0031	.0002	.0005	.0032	.0035	.0037	.0301	33222	1080	35980	286	40
41	.0028	.0002	.0004	.0029	.0031	.0033	.0244	40984	1320	54095	323	41
42	.0025	.0002	.0004	.0026	.0028	.0030	.0195	51282	1660	85128	357	42
43	.0022	.0002	.0003	.0023	.0025	.0026	.0153	63560	2140	135870	400	43
44	.0020	.0001	.0003	.0020	.0022	.0024	.0124	80645	2590	208870	455	44

Table 3.5. Typical round magnetic wire gauges in mm

Rated diameter [mm]	Insulated wire diameter [mm]
0.3	0.327
0.32	0.348
0.33	0.359
0.35	0.3795
0.38	0.4105
0.40	0.4315
0.42	0.4625
0.45	0.4835
0.48	0.515
0.50	0.536
0.53	0.567
0.55	0.5875
0.58	0.6185
0.60	0.639
0.63	0.6705
0.65	0.691
0.67	0.7145
0.70	0.742
0.71	0.7525
0.75	0.7949
0.80	0.8455
0.85	0.897
0.90	0.948
0.95	1.0

1.00	1.051
1.05	1.102
1.10	1.153
1.12	1.173
1.15	1.2035
1.18	1.2345
1.20	1.305
1.25	1.325
1.30	1.356
1.32	1.3765
1.35	1.407
1.40	1.4575
1.45	1.508
1.50	1.559

If A_{con} is larger than 30 to 40 mm² (that is 6 to 8, 2.5 mm diameter wires in parallel), rectangular conductors are recommended.

In many countries rectangular conductor cross sections are also standardized. In some cases small cross sections such as (0.8 to 2)-2 mm × mm or (0.8 to 6) × 6 mm × mm.

In general the rectangular conductor height a is kept low ($a < 3.55$ mm) to reduce the skin effect; that is, to keep the a.c. resistance low. A large cross section area of 3.55 × 50 mm × mm would be typical for large power IMs.

The rotor cage is generally made of aluminum: die-casted aluminum in low power IMs (up to 300 kW or so) or of aluminum bars attached through brazing or welding processes to end rings.

Fabricated rotor cages are made of aluminum or copper alloys and of brass (the upper cage of a double cage) for powers above 300 kW in general. The casting process of aluminum uses the rotor lamination stack as a partial mold because the melting point of silicon steel is much higher than that of aluminum. The electrical resistivity of aluminium $\rho_{\text{Al}} \cong (2.7\text{-}3.0)10^{-8} \Omega\text{m}$ and varies with temperature as shown in (3.19).

Although the rotor cage bars are insulated from the magnetic core, most of the current flows through the cage bars as their resistivity is more than 20 to 30 times smaller than that of the laminated core.

Insulated cage bars would be ideal, but this would severely limit the rotor temperature unless a special high temperature (high cost) insulation coating is used.

3.5. INSULATION MATERIALS

The primary purpose of stator insulation is to withstand turn-to-turn, phase-to-phase and phase-to-ground voltage such that to direct the stator phase currents through the desired paths of stator windings.

Insulation serves a similar purpose in phase-wound rotors whose phase leads are connected to insulated copper rings and then through brushes to stationary devices (resistances or/and special power electronic converters). Insulation is required to withstand voltages associated to: brush rigging (if any)

winding connections, winding leads and auxiliaries such as temperature probes and bearings (especially for PWM inverter drives).

The stator laminations are insulated from each other by special coatings (0.013 mm thick) to reduce eddy current core losses.

In standard IMs the rotor (slip) frequency is rather small and thus interlamination insulation may not be necessary, unless the IM is to work for prolonged intervals at large slip values.

For all wound-rotor motors, the rotor laminations are insulated from each other. The bearing sitting is insulated from the stator to reduce the bearing (shaft) voltage (current), especially for large power IMs whose stator laminations are made of a few segments thus allowing a notable a.c. axial flux linkage. This way premature bearing damage may be prevented and even so in PWM inverter fed IMs, where additional common voltage mode superhigh frequency capacitor currents through the bearings occur (Chapter 21).

Stator winding insulation systems may be divided in two types related to power and voltage level.

- Random-wound conductor IMs-with small and round conductors
- Form-wound conductor IMs-with relatively large rectangular conductors

Insulation systems for IMs are characterized by voltage and temperature requirements. The IM insulation has to withstand the expected operating voltages between conductors, (phase) conductors and ground, and phase to phase.

The American National Standards Institute (ANSI) specifies that the insulation test voltage shall be twice the rated voltage plus 100 V applied to the stator winding for 1 minute.

The heat produced by the winding currents and the core losses causes hot-spot temperatures that have to be limited in accordance to the thermal capability of the organic (resin) insulation used in the machine, and to its chemical stability and capability to prevent conductor to conductor, conductor to ground short-circuits during IM operation.

There is continuous, but slow deterioration of the organic (resin) insulation by internal chemical reaction, contamination, and chemical interactions. Thermal degradation develops cracks in the enamel, varnish, or resin, reducing the dielectric strength of insulation.

Insulation materials for electric machines have been organized in stable temperature classes at which they are able to perform satisfactorily for the expected service lifetime.

The temperature classes are (again)

Class A: 105°C

Class B: 130°C

Class F: 155°C

Class G: 180°C

The main insulation components for the random-wound coil windings are the enamel insulation on the wire, the insulation between coils and ground/slot walls-slot liner insulation, and between phases (Figure 3.7).

The connections between the coils of a phase and the leads to the terminal box have to be insulated. Also the binding cord used to tie down endwindings to reduce their vibration is made of insulation materials.

Random-wound IMs are built for voltages below 1 kV. The moderate currents involved can be handled by wound conductors (eventually a few in parallel) where enamel insulation is the critical component. To apply the enamel, the wire is passed through a solution of polymerizable resin and into the high-curing temperature tower where it turns into a thin, solid, and flexible coating.

3.5.1. Random-wound IM insulation

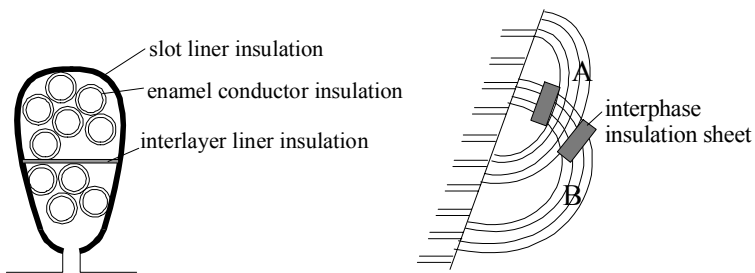


Figure 3.7 Random-wound coils insulation

Several passes are required for the desired thickness (0.025 mm thick or so). There are dedicated standards that mention the tests on enamel conductors (ASTMD-1676; ASTM standards part 39 electric insulation-test methods: solids and solidifying liquids should be considered for the scope).

Enamel wire, stretched and scraped when the coils are introduced into the slots, should survive this operation without notable damage to the enamel. Some insulation varnish is applied over the enamel wire after the stator winding is completed. The varnish provides additional enamel protection against moisture, dirt, and chemical contamination and also provides mechanical support for the windings.

Slot and phase-to-phase insulation for class A temperatures is a somewhat flexible sheet material (such as cellulose paper), 0.125 to 0.25 mm thick, or a polyester film. In some cases fused resin coatings are applied to stator slot walls by electrostatic attraction of a polymerizable resin powder. The stator is heated to fuse and cure the resin to a smooth coating.

For high temperature IMs (class F, H), glass cloth mica paper or asbestos treated with special varnishes are used for slot and phase-to-phase insulation. Varnishes may interact with the enamel to reduce the thermal stability. Enamels and varnishes are tested separately according to ASTM (D2307, D1973, D3145) and IEC standards and together.

Model motor insulation systems (motorettes) are tested according to IEEE standards for small motors.

All these insulation accelerated life tests involve the ageing of insulation test specimens until they fail at temperatures higher than the operating temperature of the respective motor. The logarithms of the accelerated ageing times are then graphed against their reciprocal Kelvin test temperatures (Arrhenius graph). The graph is then extrapolated to the planned (reduced) temperature to predict the actual lifetime of insulation.

3.5.2. Form-wound windings

Form-wound windings are employed in high power IMs. The slots are rectangular and so are the conductors. The slot filling factor increases due to this combination.

The insulation of the coil conductors (turns) is applied before inserting the coils in slots. The coils are vacuum also impregnated outside the machine. The slot insulation is made of resin-bonded mica applied as a wrapper or tape with a fibrous sheet for support (in high voltage IMs above 1 to 2 kV).

Vacuum impregnation is done with polymerizable resins which are then cured to solids by heating. During the cure, the conductors may be constrained to size to enter the slot as the epoxy-type resins are sufficiently elastic for the scope.

Voltage, through partial discharges, may cause insulation failure in higher voltage IMs. Incorporating mica in the major insulation schemes solves this problem to a large degree.

A conducting paint may be applied over the slot portion of the coils to fill the space between the insulated preformed coil and slot wall, to avoid partial discharges. Lower and medium voltage coil insulation is measured in accelerated higher temperature tests (IEEE standard 275) by using the model system called formette. Formette testing is similar to motorette testing for random-wound IMs [15].

Diagnostic nondestructive tests to check the integrity and capability of large IM insulation are also standardized [15 - 17].

3.6. SUMMARY

- The three main materials used to build IMs are of magnetic, electric, and insulation type.
- As the IM is an a.c. machine, reducing eddy current losses in its magnetic core is paramount.
- It is shown that these losses increase with the soft magnetic sheet thickness parallel to the external a.c. field.
- Soft magnetic materials (silicon steel) used in thin laminations (0.5 mm thick up to 200Hz) have low hysteresis and eddy current losses (about or less 2 W/kg at 1 T and 60 Hz).
- Besides losses, the B-H (magnetization) curve characterizes a soft magnetic material.

- The magnetic permeability $\mu = B/H$ varies from (5000 to 8000) μ_0 at 1T to (40 to 60) μ_0 at 2.0 T in modern silicon steel laminations. High permeability is essential to low magnetization (no load) current and losses.
- High speed IMs require frequencies above 300 Hz (and up to 800 Hz and more). Thinner silicon lamination steels with special thermal treatments are required to secure core losses in the order of 30-50 W/kg at 800 Hz and 1 T.
- 6.5% silicon steel lamination for small IMs have proven adequate to reduce core losses by as much as 40% at 50 (60) Hz.
- Also, interspersing oriented grain (transformer) laminations (0.35 mm thick) with orthogonal orientation laminations has been shown to produce a 30 to 40% reduction in core losses at 50 (60) Hz and 1T in comparison with 0.5 mm thick nonoriented grain silicon steel used in most IMs.
- Soft magnetic composites have been introduced and shown to produce lower losses than silicon steel laminations only above 300Hz, but at the expense of lower permeability ((100 to 200) μ_0 in general). Cold compression methods are expected to increase slot filling factor notably and thus increase the current loading. Size reduction is obtained also due to the increase of heat transmissivity through soft magnetic composites.
- Electric conductors for stator windings and for wound rotors are made of pure (electrical) copper.
- Cast aluminum is used for rotor cage windings up to 300kW.
- Fabricated aluminum or copper bars and rings are used for higher power IM cage rotors.
- The rotor cage bars are not, in general, insulated from the rotor lamination core. Interbar currents may thus occur.
- The windings are made out of random-wound coils with round wire, and of form-wound coils for large IMs with rectangular wire.
- The windings are insulated from the magnetic core through insulation materials. Also, the conductors are enameled to insulate one conductor from another.
- Insulation systems are classified according temperature limits in four classes: Class A-105°C, Class B-130°C, Class F-155°C, Class G-180°C.
- Insulation testing is thoroughly standardised as the insulation breakdown finishes the operation life of an IM through short-circuit.
- Thinner and better insulation materials keep surfacing as they are crucial to better performance IMs fed from the power grid and from PWM inverters.

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